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ASSESSMENT AND IMPROVEMENT OF A SCANNING LIDAR LASER BEAM POSITIONING ACCURACY

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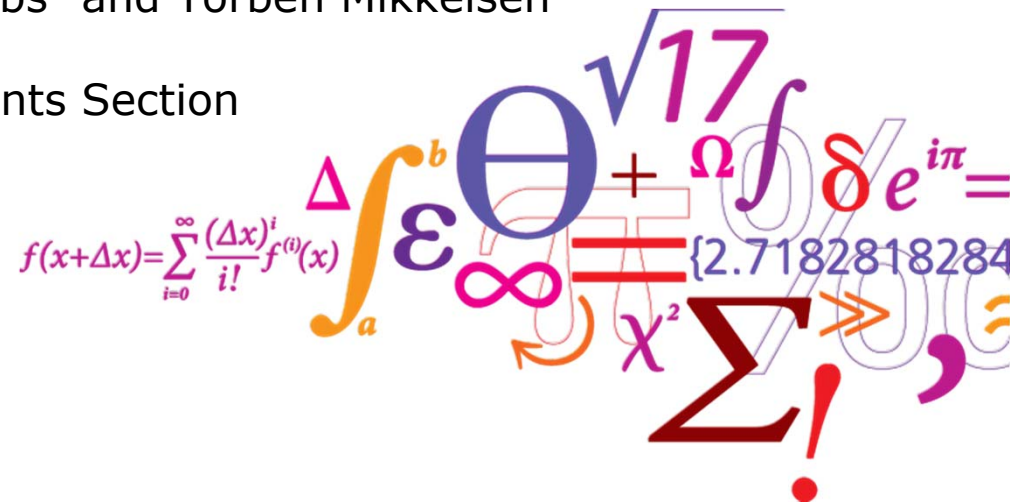
Jon Howard², Keith Relleen², Tony Jacobs³ and Torben Mikkelsen¹

¹DTU Wind Energy, Test and Measurements Section

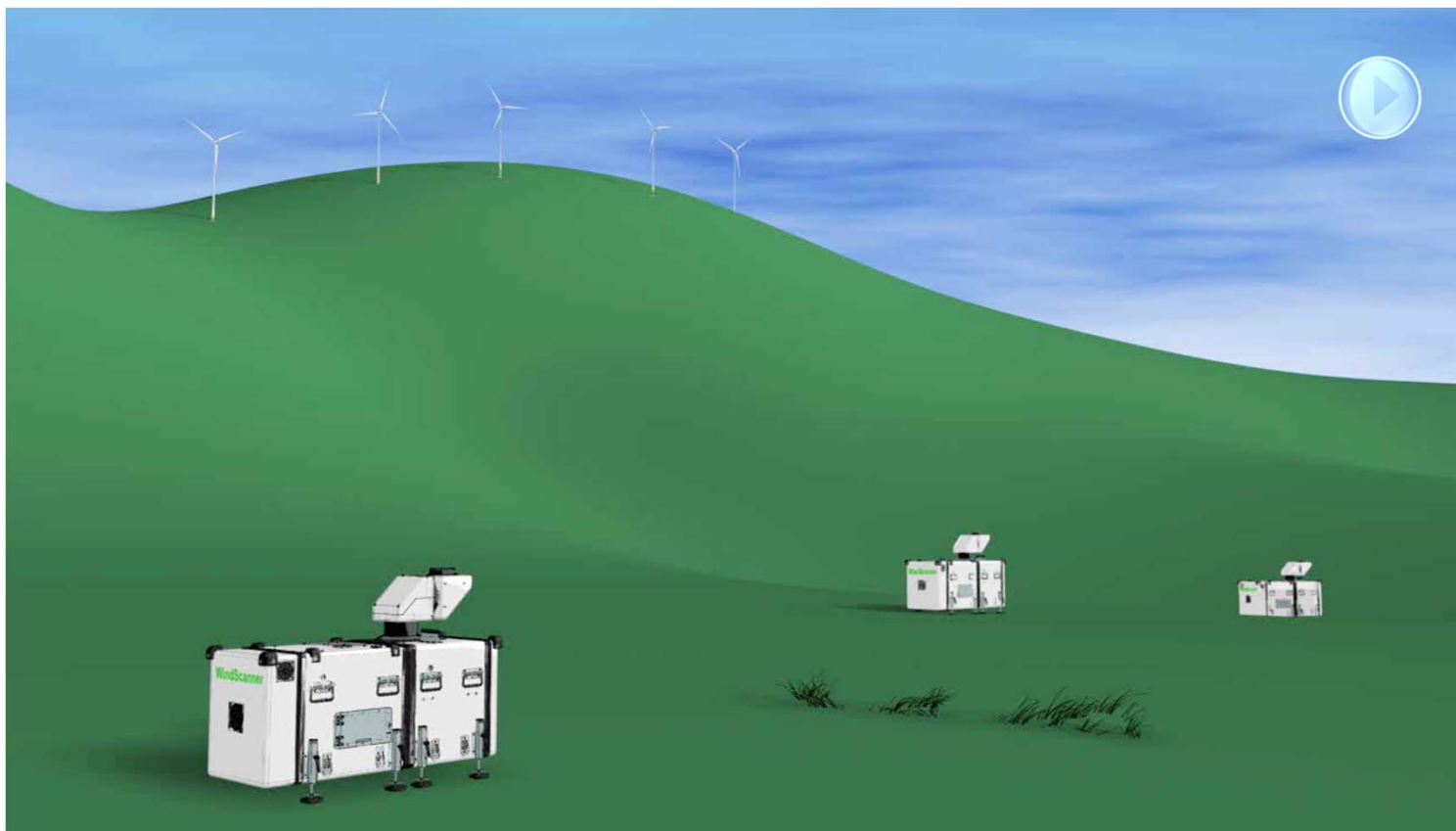
²Heason Technology Ltd.

³Delta Tau (UK) Ltd.

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Motivation



Master computer

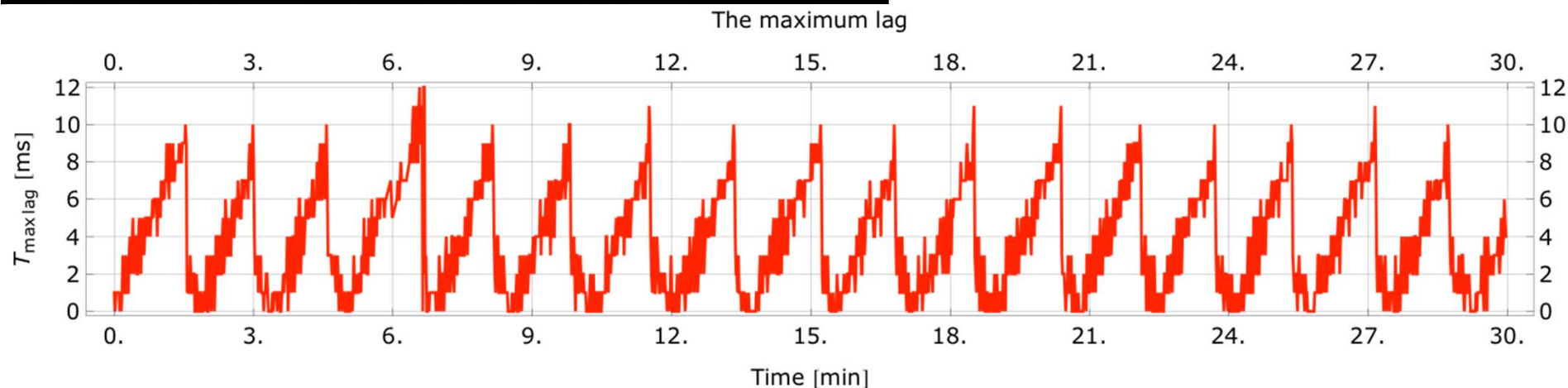
- Long-range WindScanner system
- Unified system of multiple pulsed coherent Doppler scanning lidars
- Lidars are intended to be **time-space** synchronized

Time synchronization



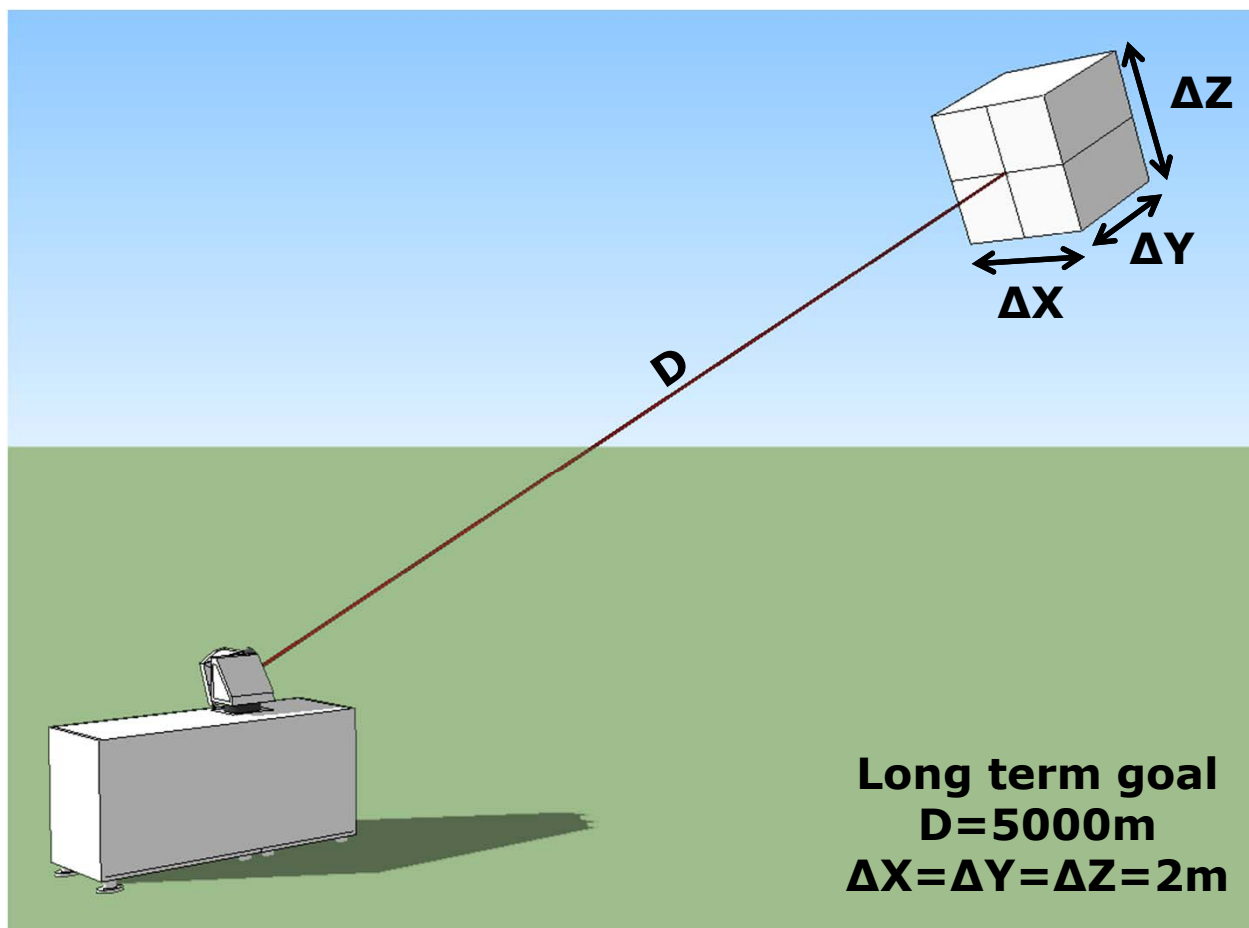
Max lag 10 ms [1] irrespective to:

- Measurement time
- Number of lidars



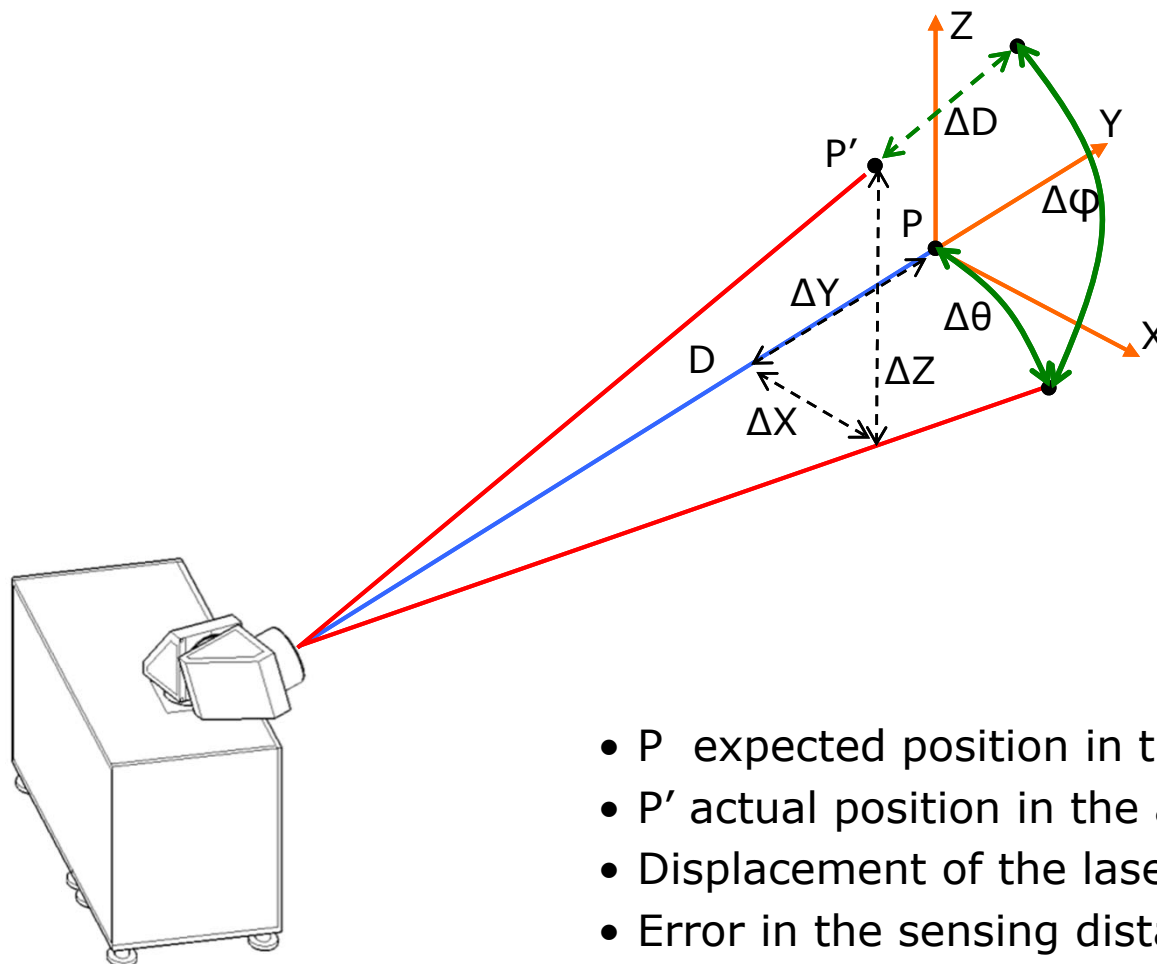
[1] Vasiljević, N. et al. (2013). "The long-range WindScanner system – how to synchronously intersect multiple laser beams"

Space synchronization



- Cube represents the volume in which we expect the center of range gate

Uncertainty in laser beam positioning



- P expected position in the atmosphere
- P' actual position in the atmosphere
- Displacement of the laser beam direction ($\Delta\theta, \Delta\phi$)
- Error in the sensing distance (ΔD)

Long term goal:

$$\Delta\theta = \Delta\phi = \pm 0.01^\circ$$

$$\Delta D = \pm 1\text{m}$$

Contributors to uncertainty

 ΔD

- Error in the measurements of laser pulse time of flight

- Position readings of the scanner head from the motor side
- Mechanical imperfections of the movable parts of the scanner head

- Gear backlash

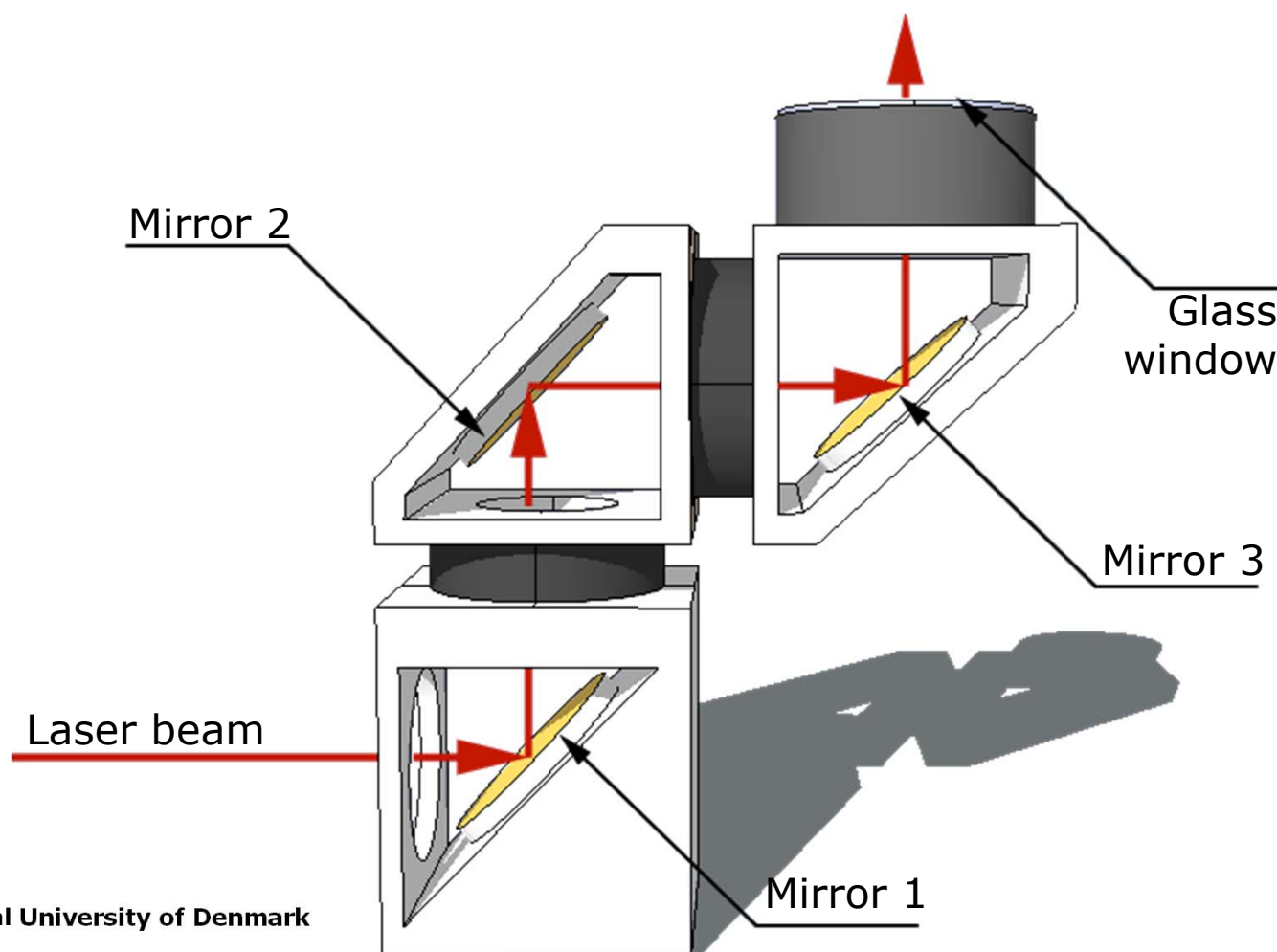
- Perpendicularity of the axes of the rotation
- Connection of the scanner head with the casing

 $\Delta \theta, \Delta \phi$

- Dynamics of the lidar
- Flatness of the mirrors surfaces
- Consistency of the reflective index of the mirrors surface and the glass window of the scanner head
- Alignment of the optical components
- Home position of the scanner head
- Leveling of the lidar during measurements
- Refractive index of the atmosphere

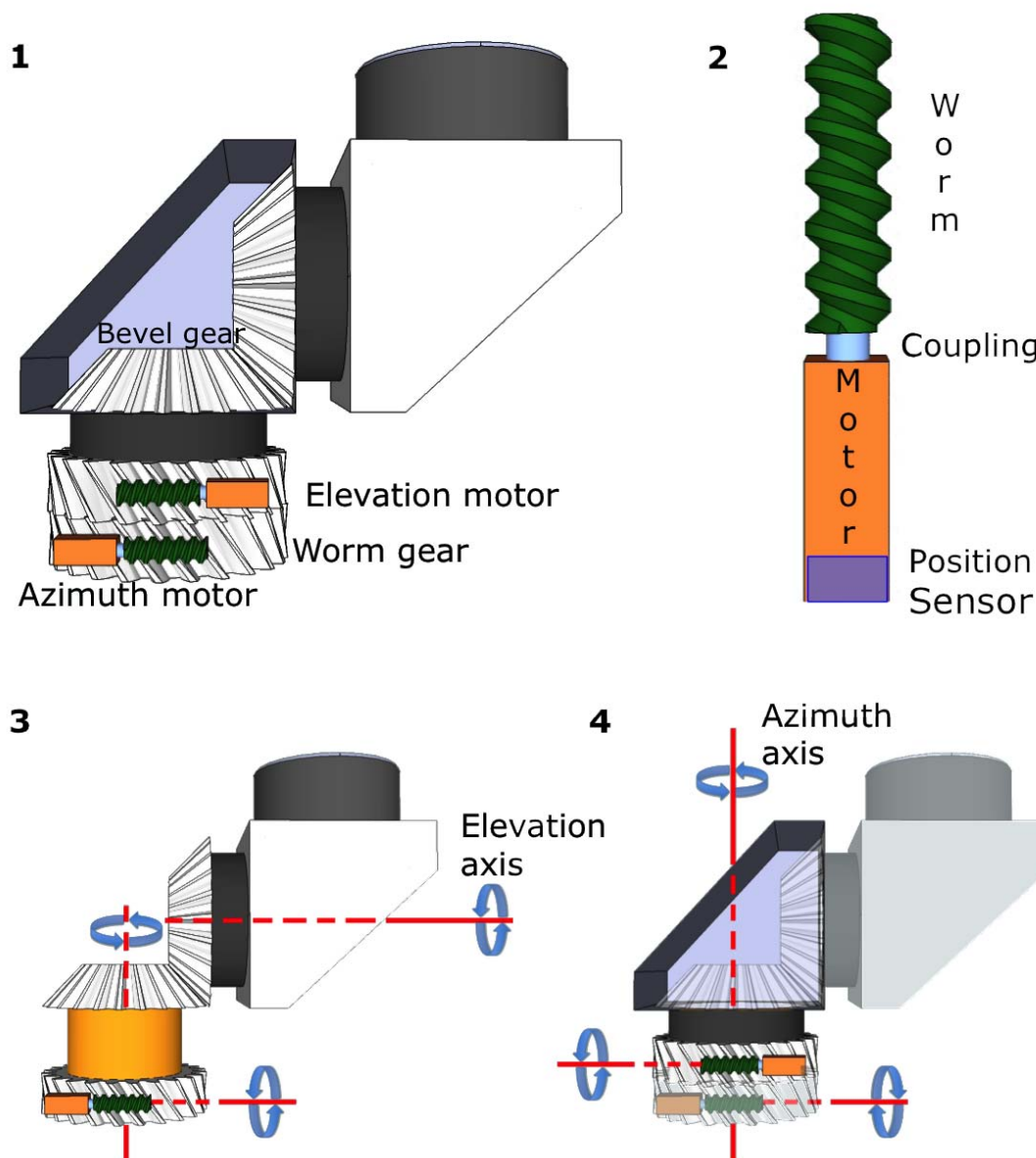
Scanner head

- Mirror-based steering



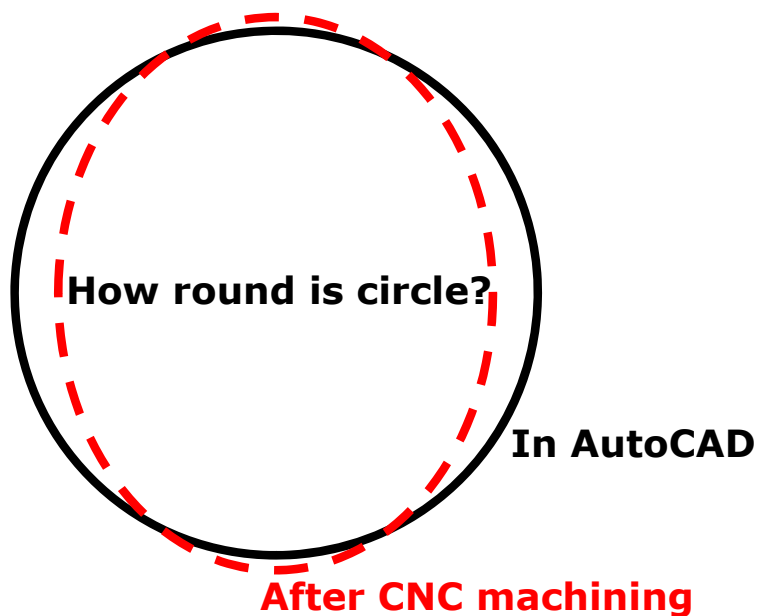
Scanner head

- Mirror-based steering
- Endless rotation
- Gear-box driven:
 - Worm
 - Worm gear
 - Bevel gears
 - ...
- Position sensors = motor encoders
- Max speed $50^{\circ}/s$
- Max acceleration $100^{\circ}/s^2$
- Resolution 0.0001°
- IP65
- Design and Development by
DTU Wind Energy and
Steen Andreasen (IPU)

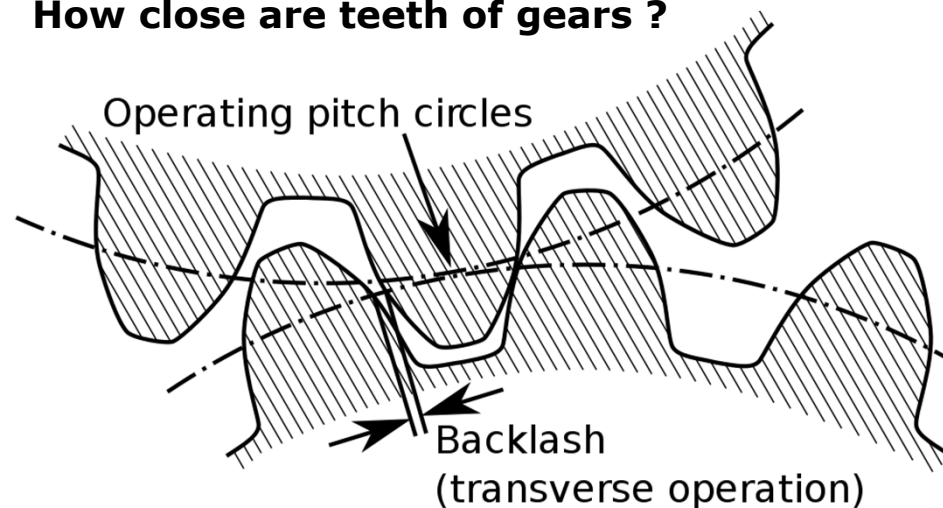


Issues with design

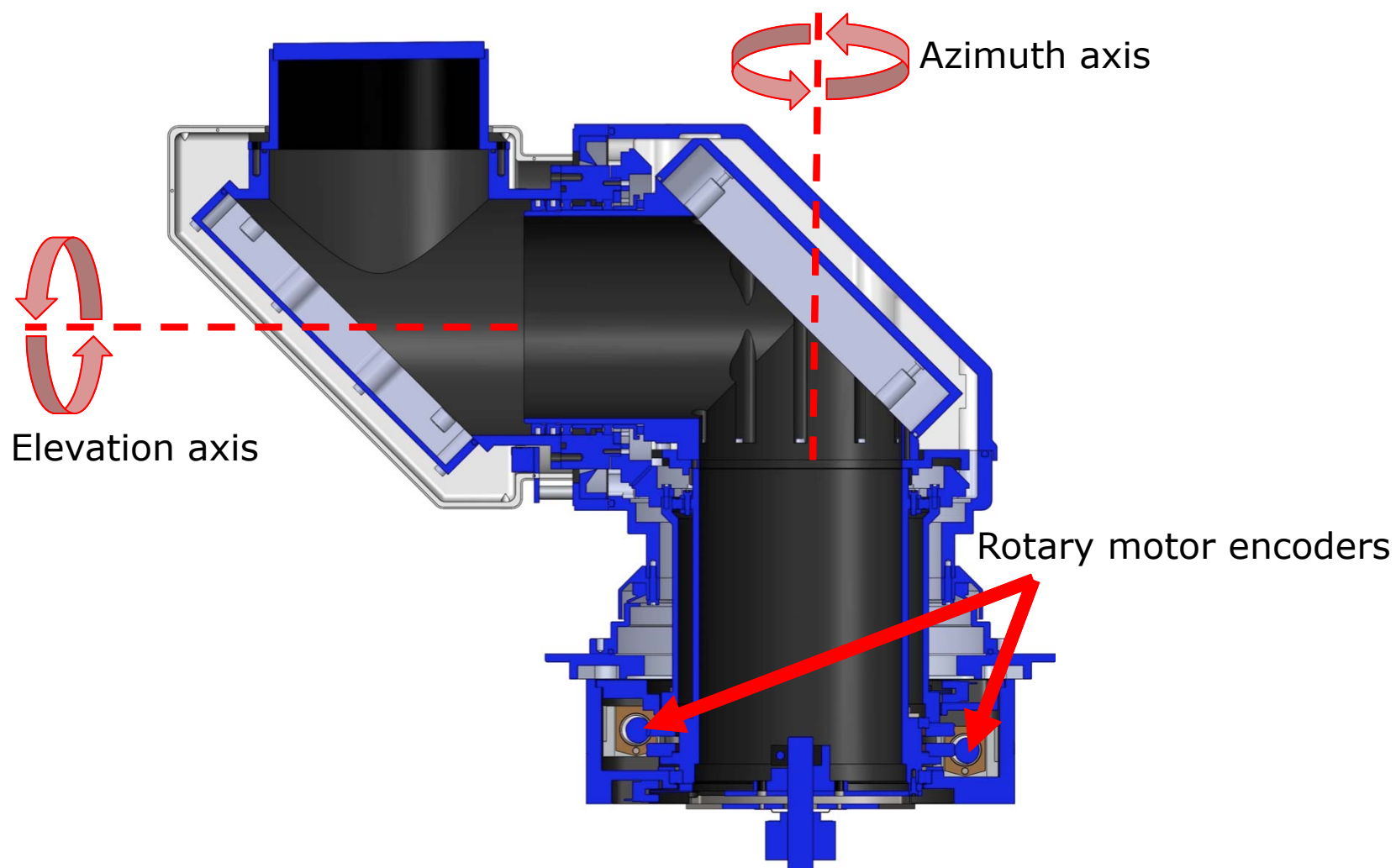
- Tolerances in manufacturing of gear-box components
- Unavoidable backlash
- Position readings from the motor side do not necessary correspond to the actual positions of the scanner head



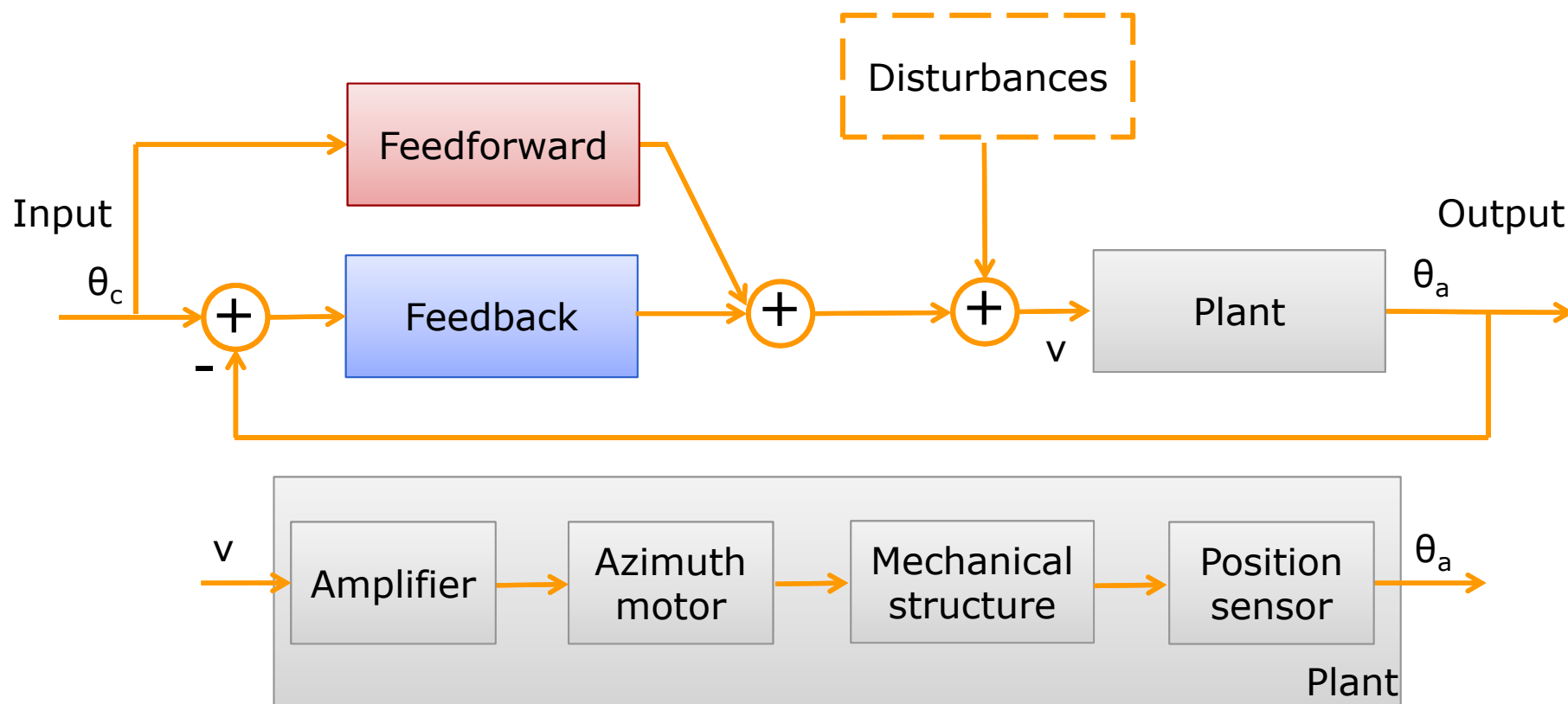
How close are teeth of gears ?



Why don't they correspond?

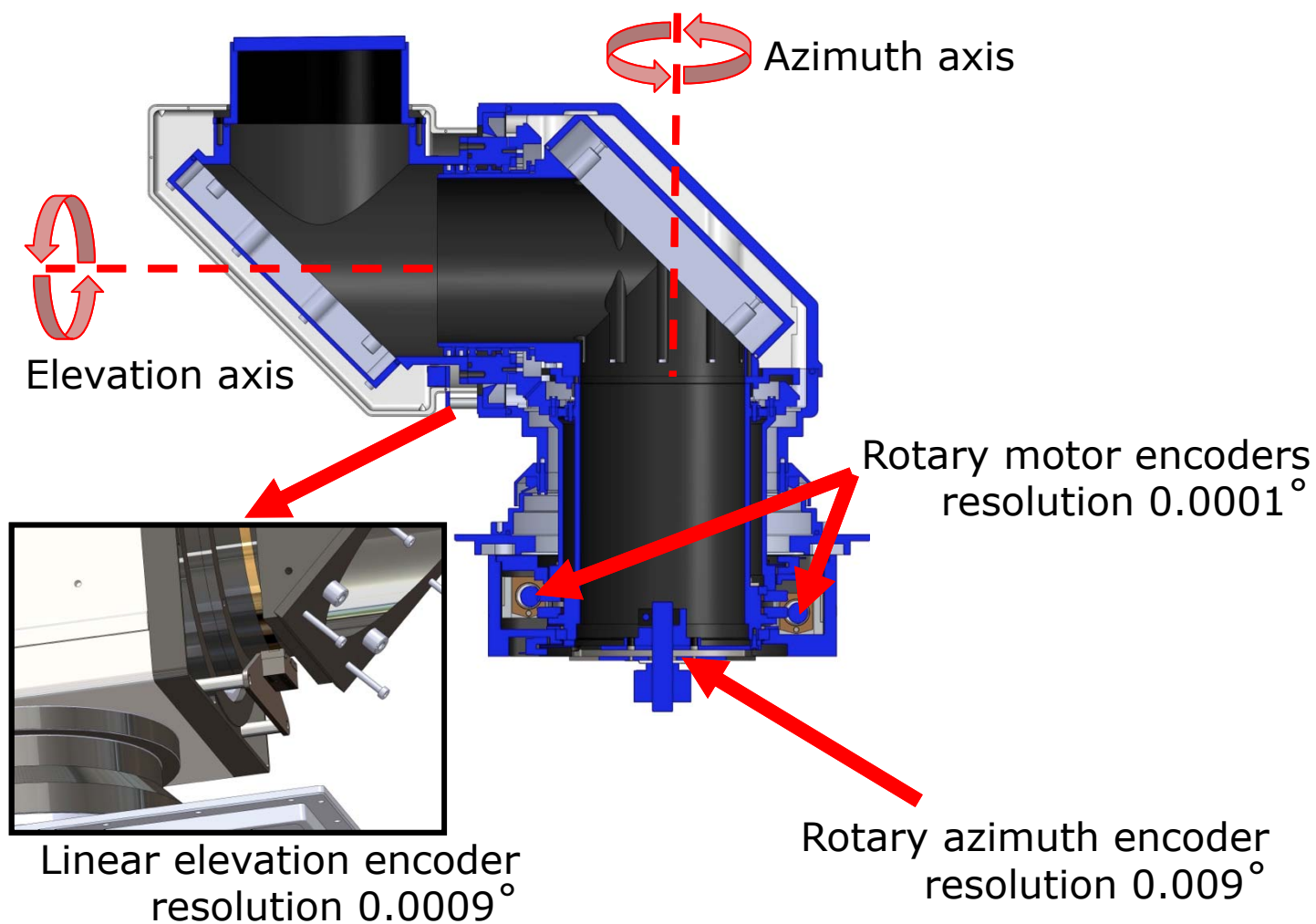


Consequences



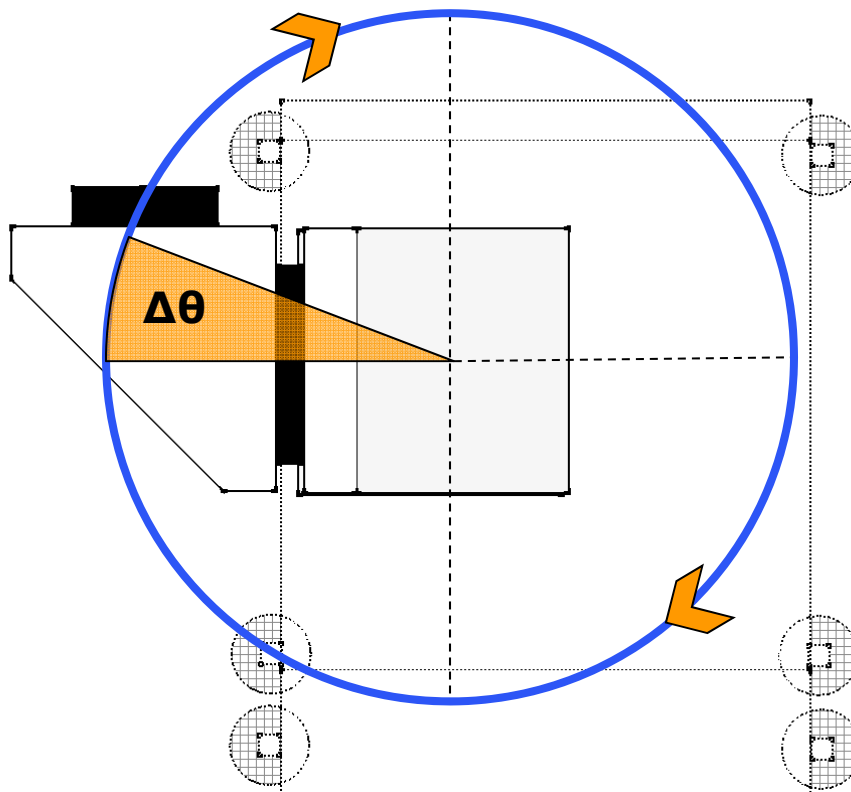
- **Feedback and feedforward parameters cannot be accurately tuned**
 - **Feedback control will not have complete information**
- => **This will reflect on the laser beam positioning accuracy!!!**

Additional sensors



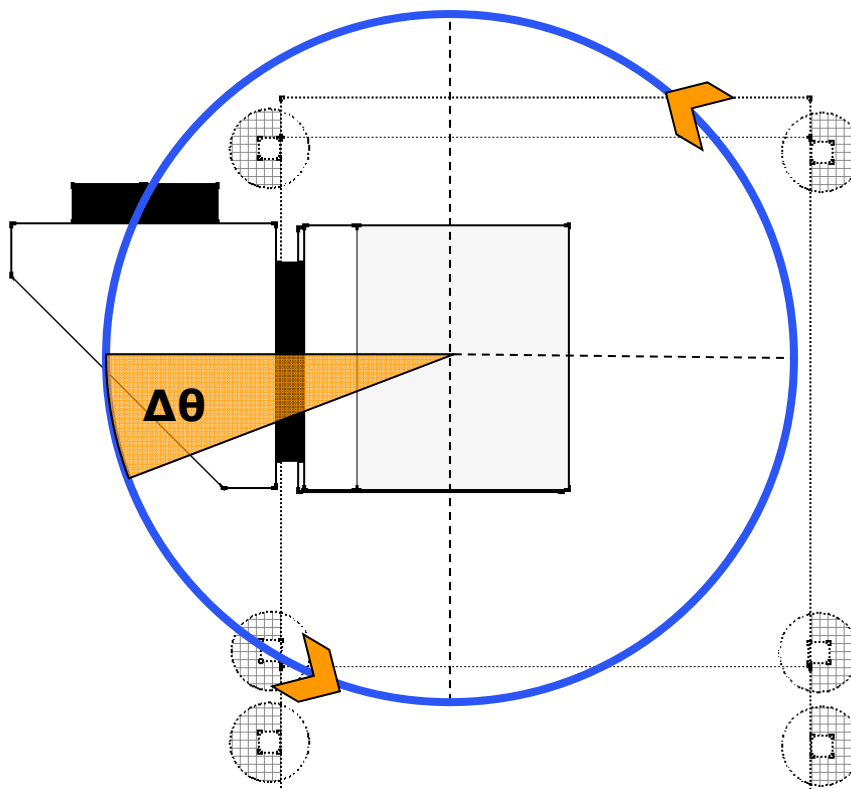
Azimuth axis test

- Clockwise rotation
- Rotate the scanner head in $\Delta\theta=10^\circ$ discrete moves for full 360°
- Wait for a few seconds for the scanner head to settle down
- Switch off the motor power
- Take the positions:
 - Commanded
 - Motor side
 - Load side (Actual)
- Calculate tracking errors:
 - Commanded – Motor position**
 - Commanded – Load position**

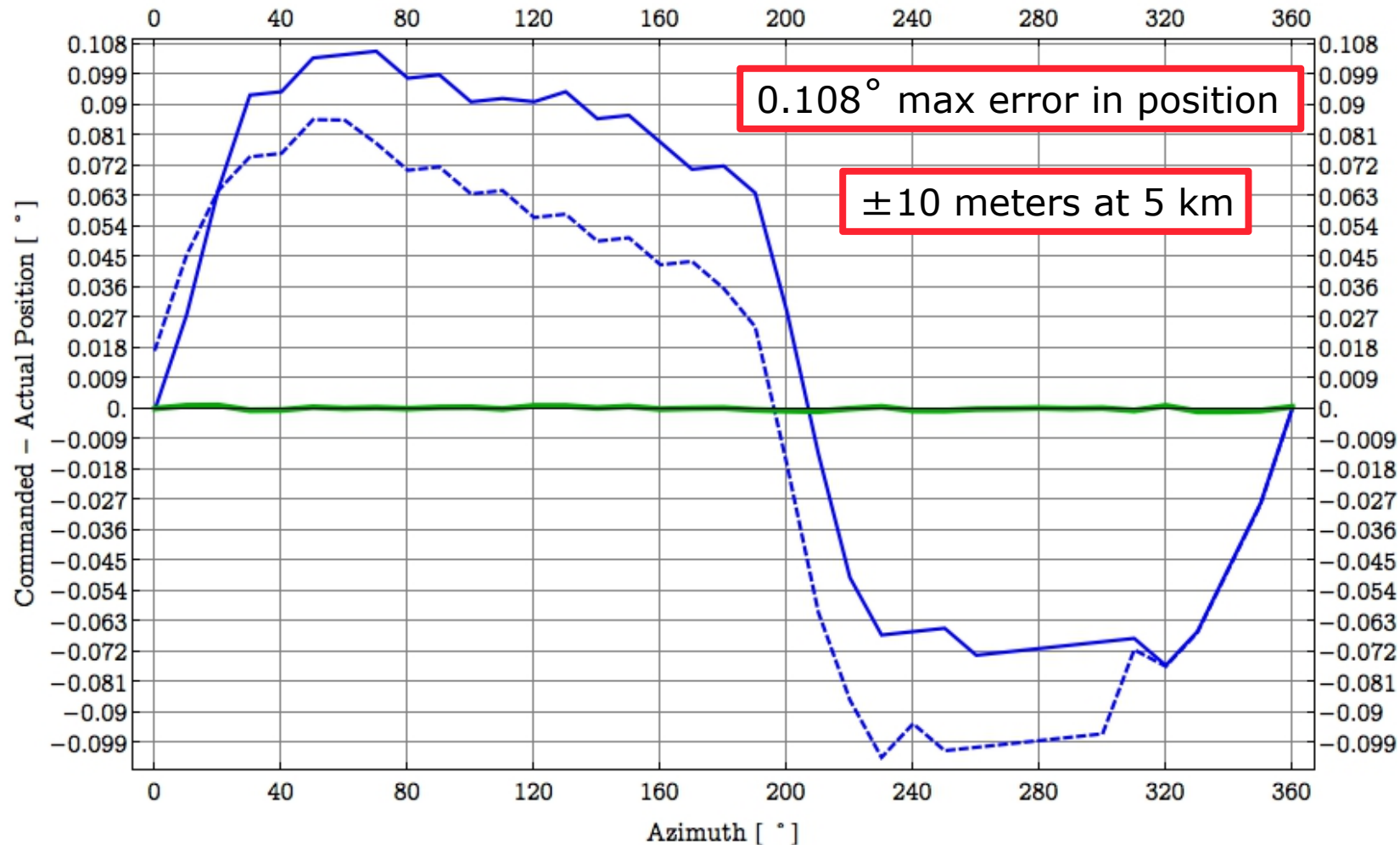


Azimuth axis test

- Anticlockwise rotation
- Rotate the scanner head in $\Delta\theta=10^\circ$ discrete moves for full 360°
- Wait for a few seconds for the scanner head to settle down
- Switch off the motor power
- Take the positions:
 - Commanded
 - Motor side
 - Load side (Actual)
- Calculate tracking errors:
 - Commanded – Motor position**
 - Commanded – Load position**

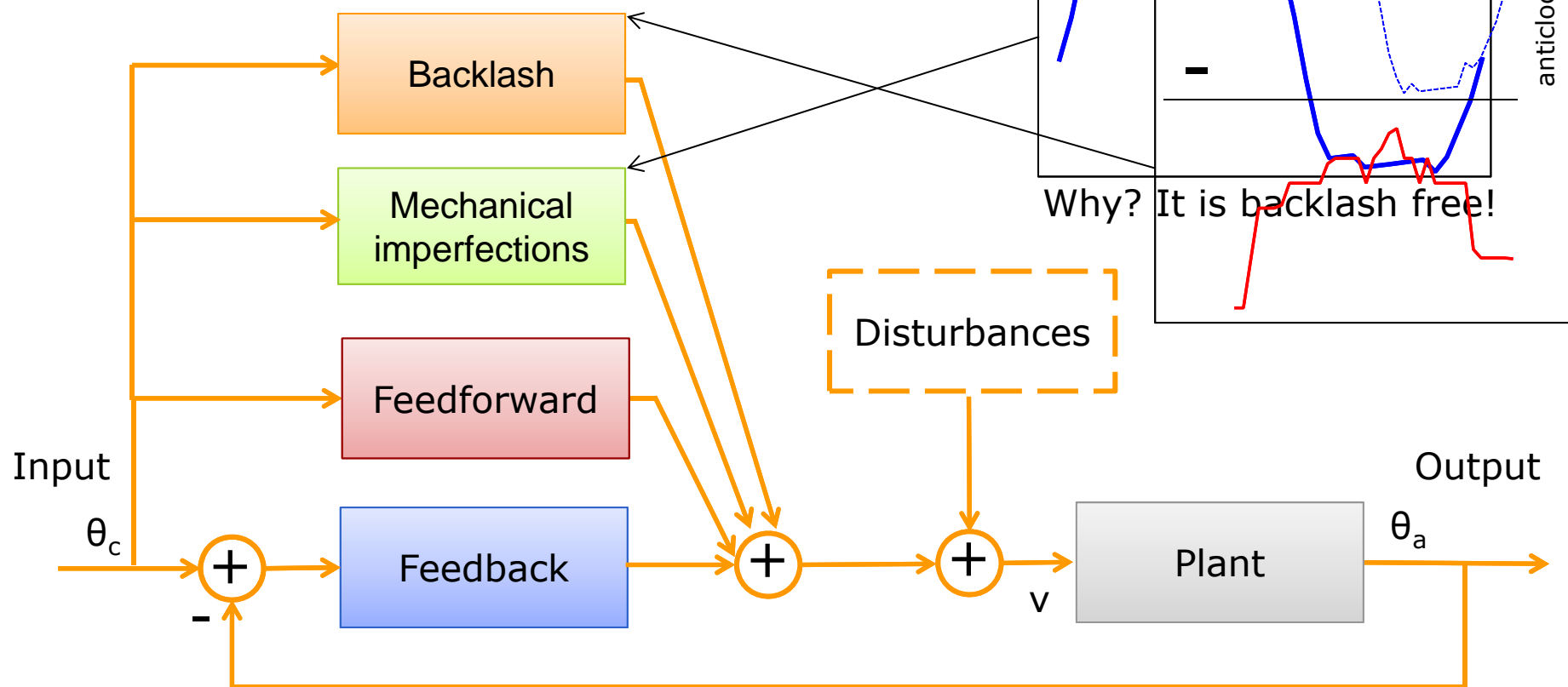


Azimuth test results

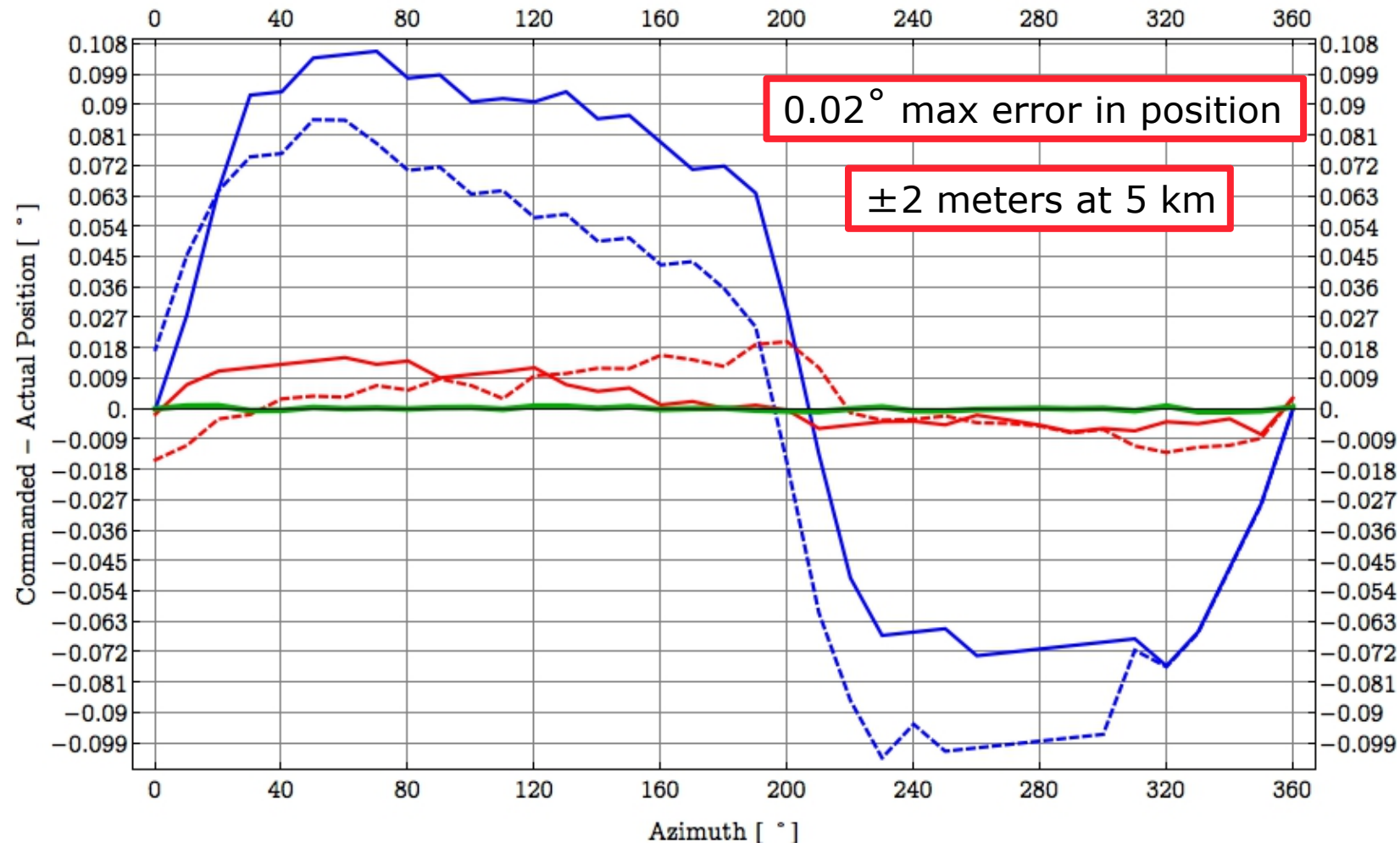


- **Solid blue line:** Commanded Position - Load Position (clockwise rotation)
- **Dashed blue line:** Commanded Position - Load Position (anticlockwise rotation)
- **Solid green line:** Commanded Position - Motor Position (bidirectional)

Improve control loop

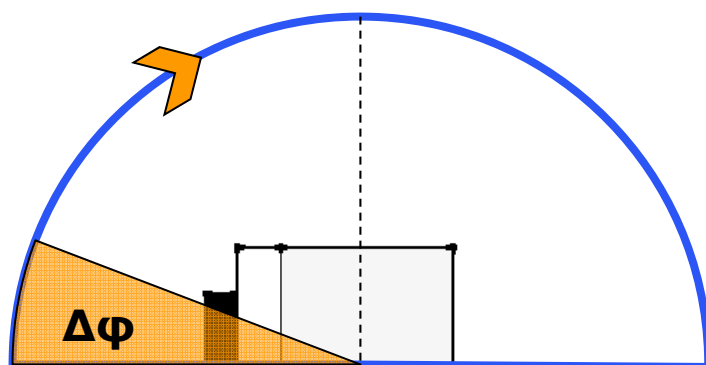


New results



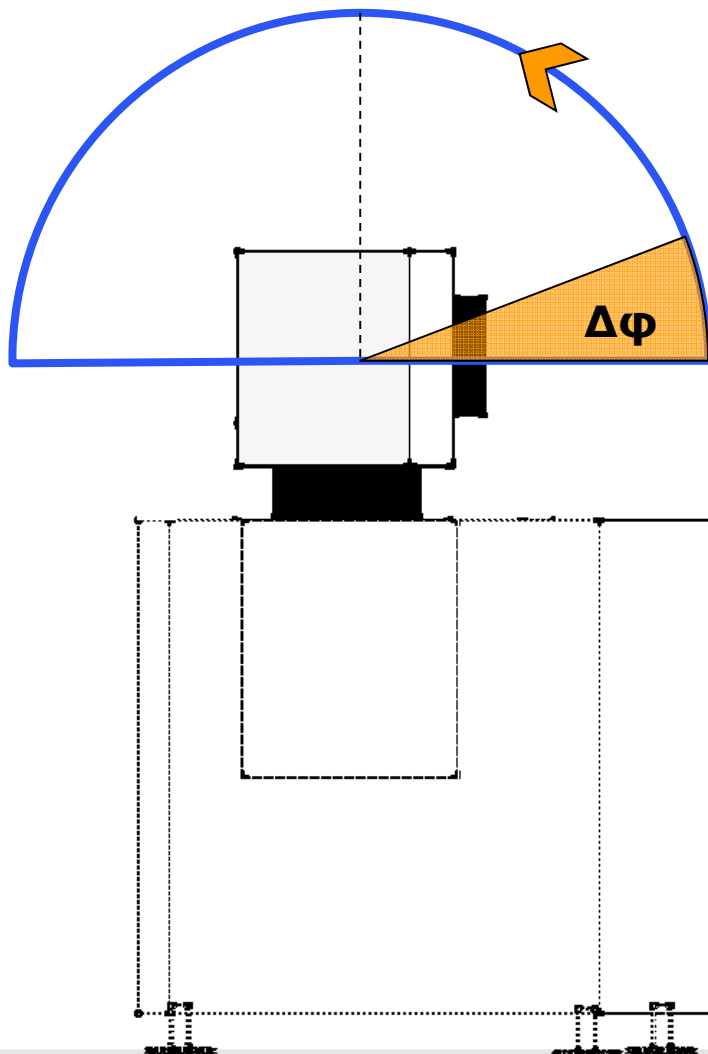
- **Solid red line:** Commanded Position - Load Position (clockwise rotation with improved control loop)
- **Dashed red line:** Commanded Position - Load Position (anticlockwise rotation with improved control loop)
- **Solid blue line:** Commanded Position - Load Position (clockwise rotation)
- **Dashed blue line:** Commanded Position - Load Position (anticlockwise rotation)
- **Solid green line:** Commanded Position - Motor Position (bidirectional)

Elevation axis test – clockwise



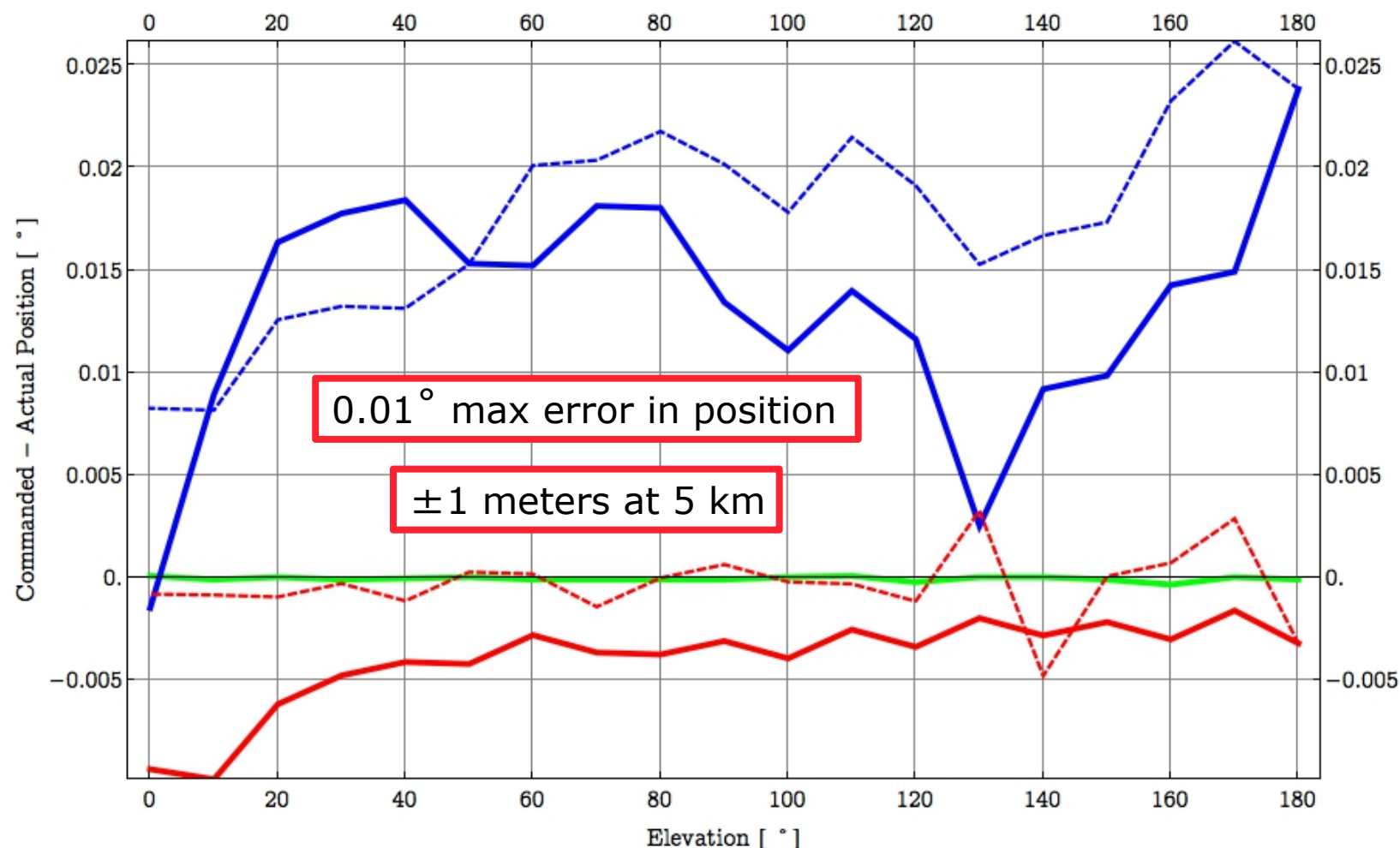
Testing procedure same as
for the azimuth axis

Elevation axis test – anticlockwise



Testing procedure same as
for the azimuth axis

Elevation results



- **Solid red line:** Commanded Position – Load Position (clockwise rotation with improved control loop)
- **Dashed red line:** Commanded Position – Load Position (anticlockwise rotation with improved control loop)
- **Solid blue line:** Commanded Position – Load Position (clockwise rotation)
- **Dashed blue line:** Commanded Position – Load Position (anticlockwise rotation)
- **Solid green line:** Commanded Position – Motor Position (bidirectional)

Conclusion

- Position readings from the motor side are killer factor for the accuracy
 - If you can, always acquire position of the scanner head from the load side:
 - Option 1 (endless rotation): slip-rings
 - Option 2 (limited rotation): avoid slip-rings and use long enough cables
 - Option 3 (gear-free) : decrease the amount of mechanical components, and go for a direct-drive design!
 - If this is not possible, use the presented method to improve the accuracy
 - Method is simple and it works
 - Method is affordable (it needs a set of accurate position sensors)
 - Mechanical imperfections modeled and integrated into the control loop
 - Backlash modeled and integrated into the control loop
 - Positioning accuracy improved up to 5 times
- ⇒ **from +/- 10 m to +/- 2 m at distance of 5 kilometers**

Thank you